



# A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with Nd<sup>3+</sup> or with Er<sup>3+</sup> ions

Alexandre Fafin, J. Cardin, Christian Dufour, Fabrice Gourbilleau

## ► To cite this version:

Alexandre Fafin, J. Cardin, Christian Dufour, Fabrice Gourbilleau. A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with Nd<sup>3+</sup> or with Er<sup>3+</sup> ions. EMRS Spring meeting 2015, May 2015, Lille, France. 2015. hal-01158504

**HAL Id: hal-01158504**

**<https://hal.science/hal-01158504>**

Submitted on 1 Jun 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with $\text{Nd}^{3+}$ or with $\text{Er}^{3+}$ ions

A. Fafin<sup>1</sup>, J. Cardin<sup>2</sup>, C. Dufour<sup>2</sup> and F. Gourbilleau<sup>2</sup>

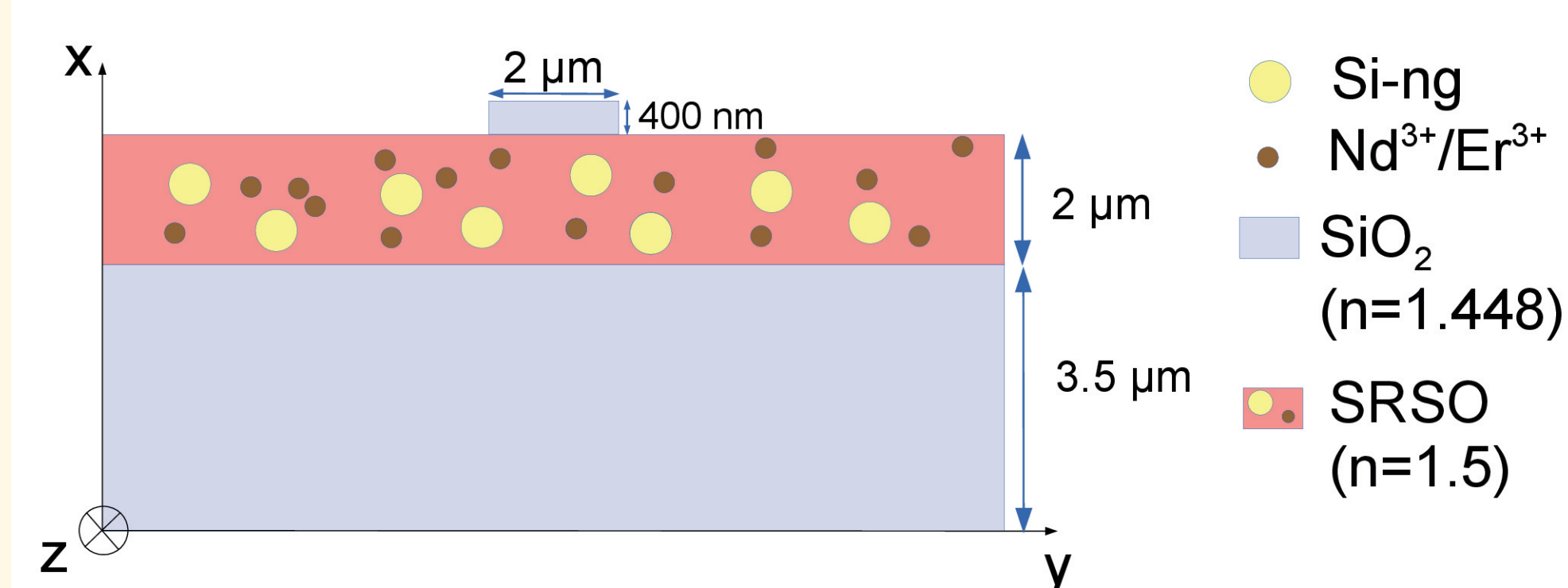
<sup>1</sup> Institut Pprime, Département Physique et Mécanique des Matériaux, UPR 3346 CNRS, Université de Poitiers, SP2MI, 11 Bvd. M. et P. Curie, BP 30179, 86962 Futuroscope Chasseneuil Cedex, France

<sup>2</sup>CIMAP, UMR CNRS/CEA/ENSICAEN/UCBN, Ensicaen, 6 Bvd Maréchal Juin, 14050 Caen Cedex 4, France, EU

e-mail: alexandre.fafin@univ-poitiers.fr

## INTRODUCTION

Goal: Compare the optical gain in a waveguide containing silicon nanograins (Si-ng) and doped with either neodymium ions ( $\text{Nd}^{3+}$ ) or erbium ions ( $\text{Er}^{3+}$ ).



Transverse section view of the waveguide. Propagation of the pump and signal along z direction inside Silicon Rich Silicon Oxide (SRSO) layer.

## NEW ADE-FDTD ALGORITHM

**Classic ADE-FDTD algorithm:** Electric field  $\mathbf{E}$ , magnetic field  $\mathbf{H}$ , polarisations  $\mathbf{P}_{ij}$  and populations  $\mathbf{N}_i$  are calculated with a unique  $\Delta t$  imposed by the FDTD method. (In visible spectral range  $\Delta t \approx 10^{-17}$  s).

➡ **10<sup>6</sup> years of calculation to reach steady state of  $\mathbf{N}_i$  on a such waveguide.**

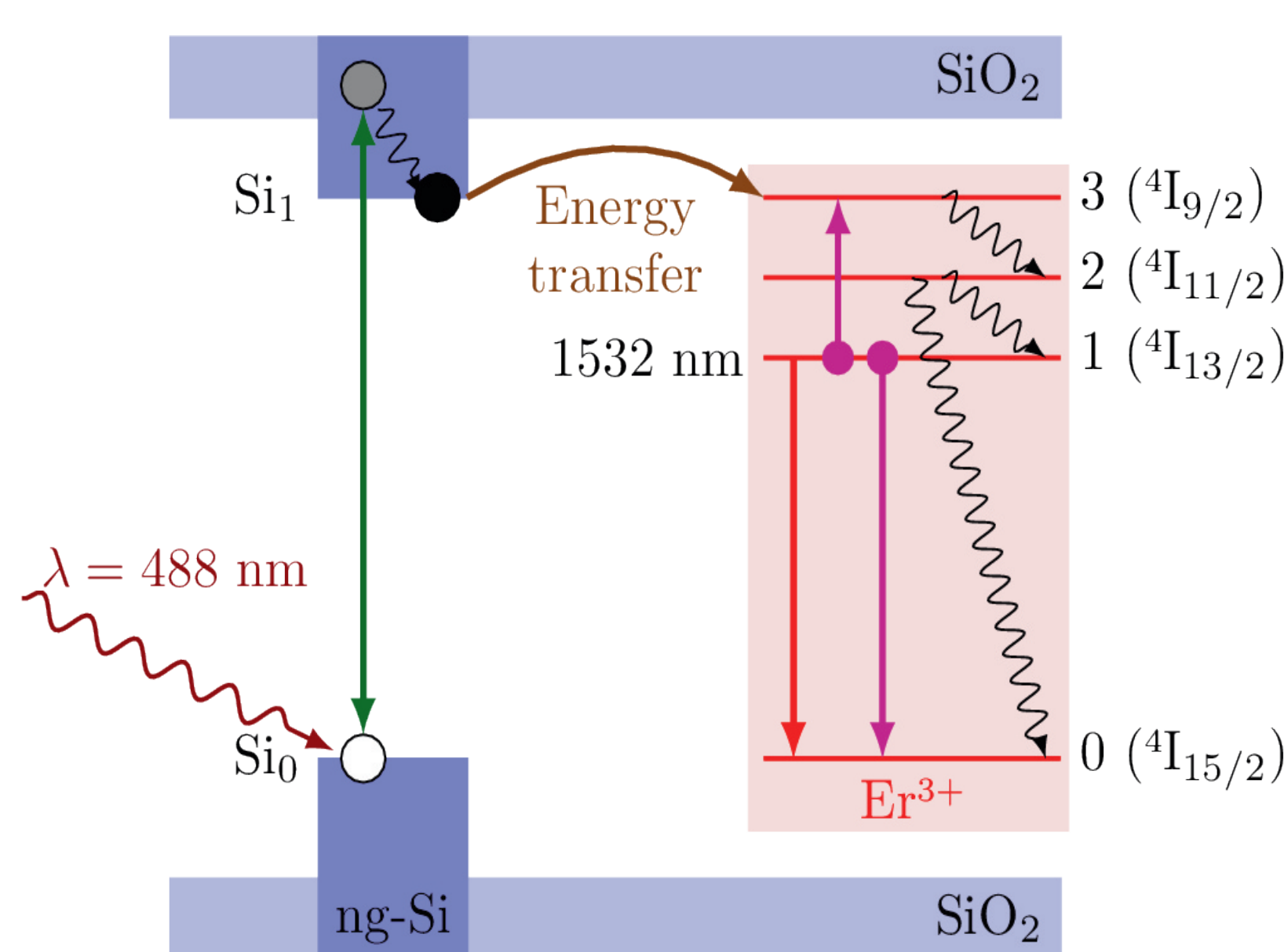
**New ADE-FDTD algorithm<sup>1</sup>:** separate loops for  $\mathbf{E}$ ,  $\mathbf{H}$  and  $\mathbf{P}$  on the one hand and populations  $\mathbf{N}_i$  on the other hand.

➡ **7 days of calculation to reach steady state of  $\mathbf{N}_i$ .**

(1) A. Fafin *et al*, "Modeling of the electromagnetic field and level populations in a waveguide amplifier: a multi-scale time problem," Opt. Express **21**, 24171-24184 (2013).

## RARE EARTH EXCITATION

### Erbium excitation mechanisms



- Modeling rare earth ions ( $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$ ) and silicon nanograins (si-ng) by a system of levels populations  $\mathbf{N}_i$ .
- Excitation of  $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$  through the Si-ng by energy transfer.

- Si-ng are excited by a pump at 488 nm.

- $w_{nr}$ : Non radiative transition

- $\downarrow$ : Radiative transition

- $\uparrow$ : Up-conversion

Erbium ions

Signal at 1532 nm :

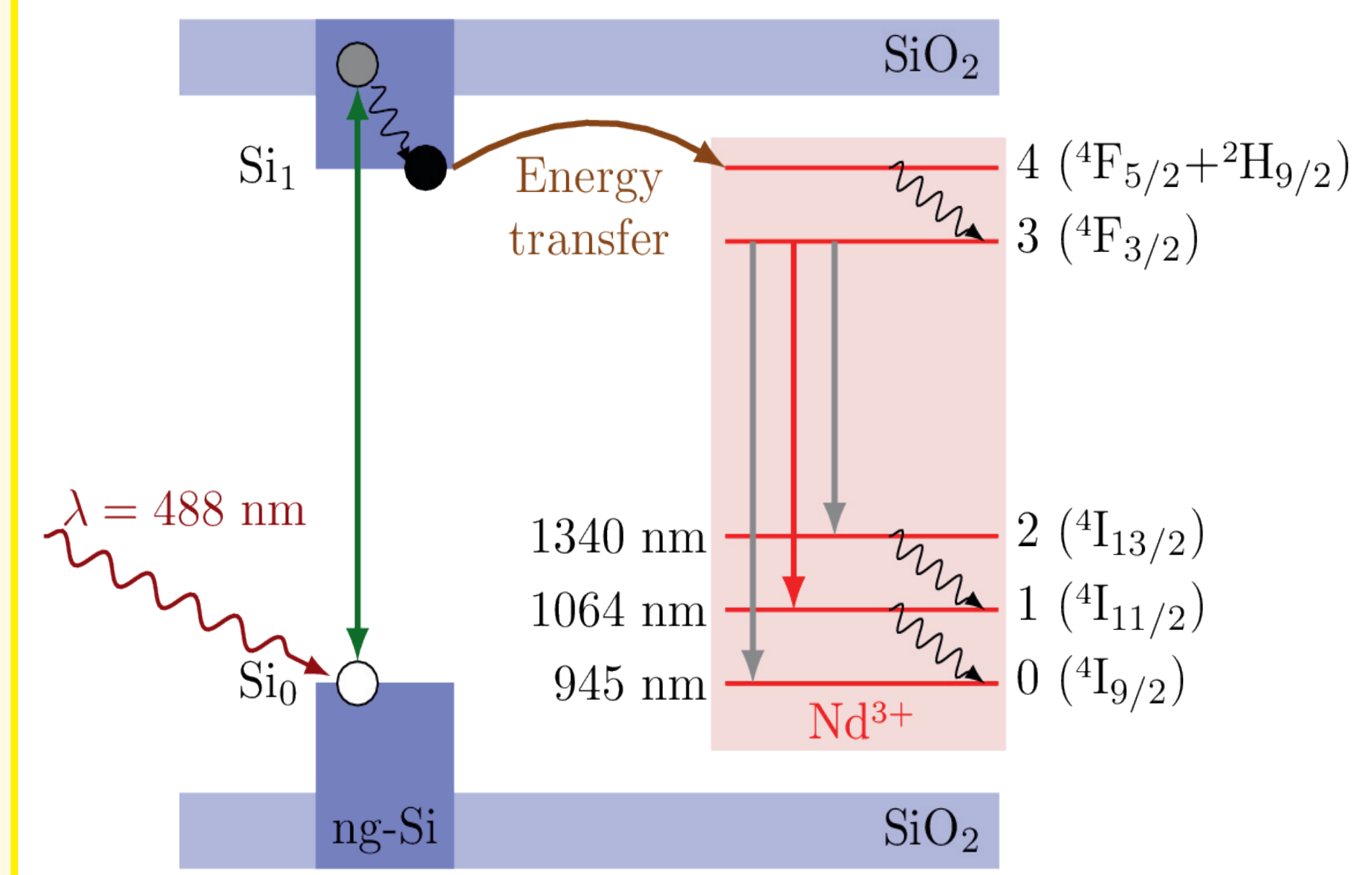
➡ Transition between  $\mathbf{N}_1$  and  $\mathbf{N}_0$

Neodymium ions

Signal at 1064 nm :

➡ Transition between  $\mathbf{N}_3$  and  $\mathbf{N}_1$

### Neodymium excitation mechanisms

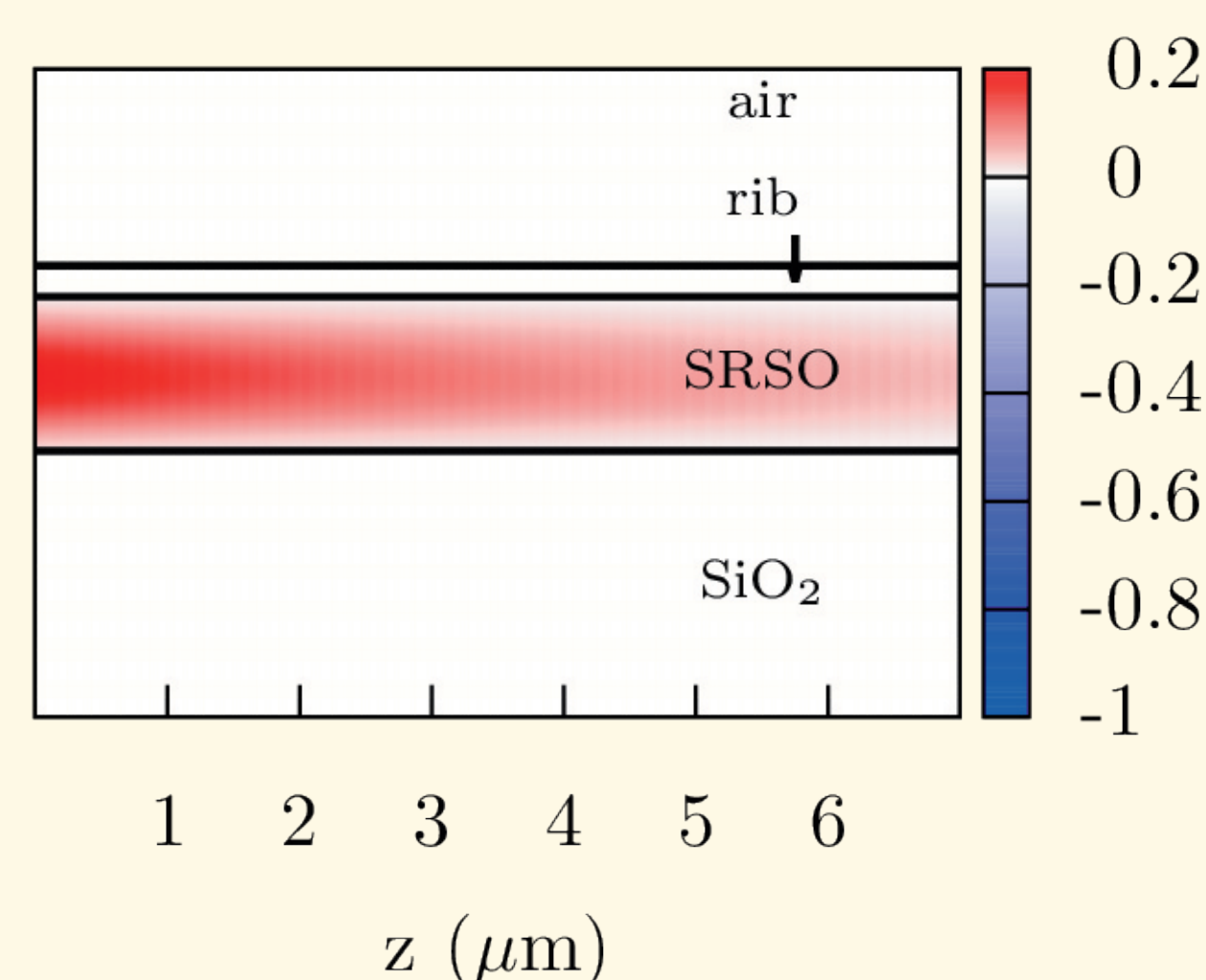
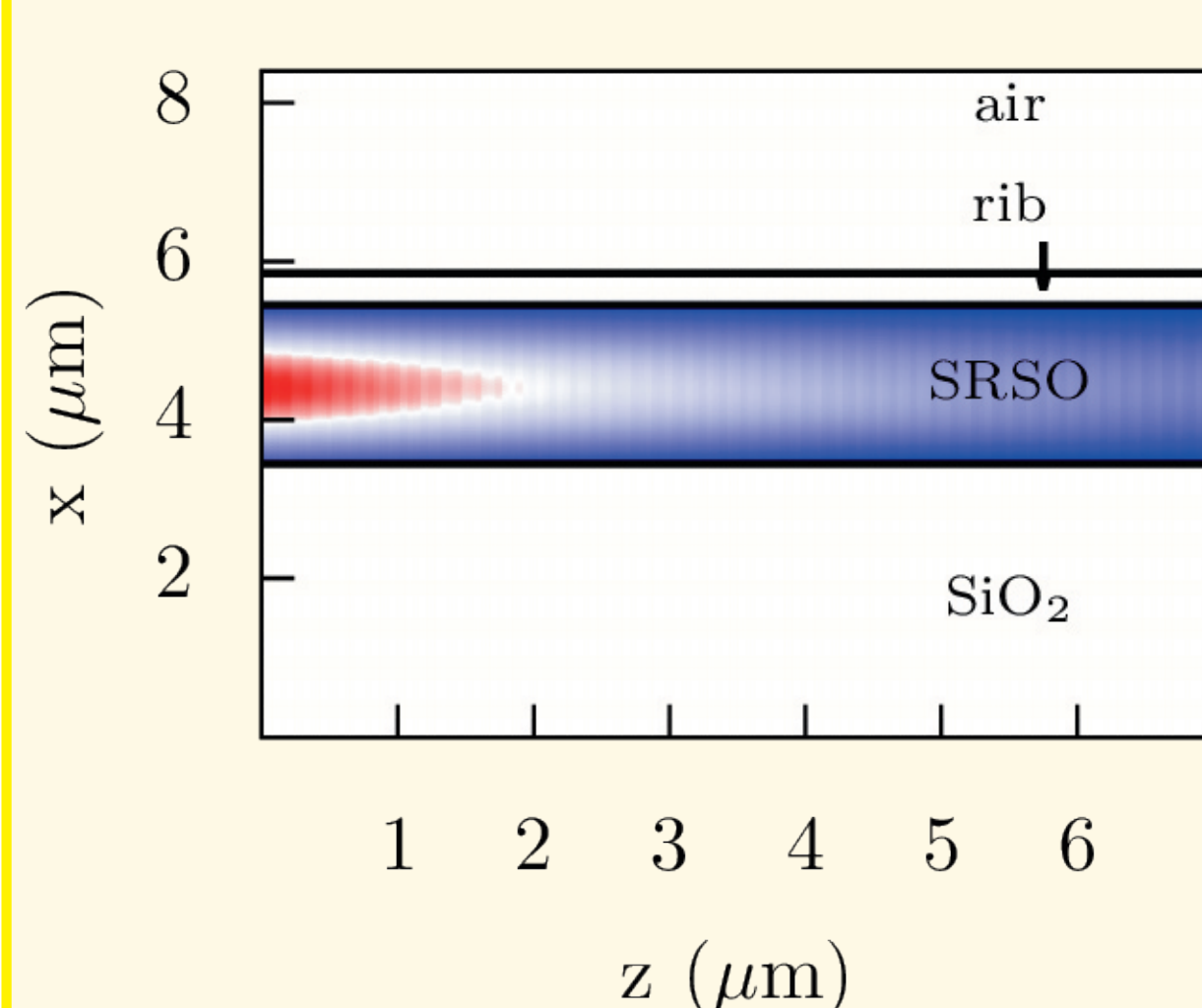


## RELATIVE POPULATION DIFFERENCE

For a pump power of 1000 mW/mm<sup>2</sup>

$$\text{Er}^{3+}: (N_1 - N_0)/N_{tot}$$

$$\text{Nd}^{3+}: (N_3 - N_1)/N_{tot}$$



Relative population difference reach population inversion only over a length of 1.5 μm.

➡  $\text{Er}^{3+}$  is a 3-level system

Relative population difference reach population inversion along the whole structure.

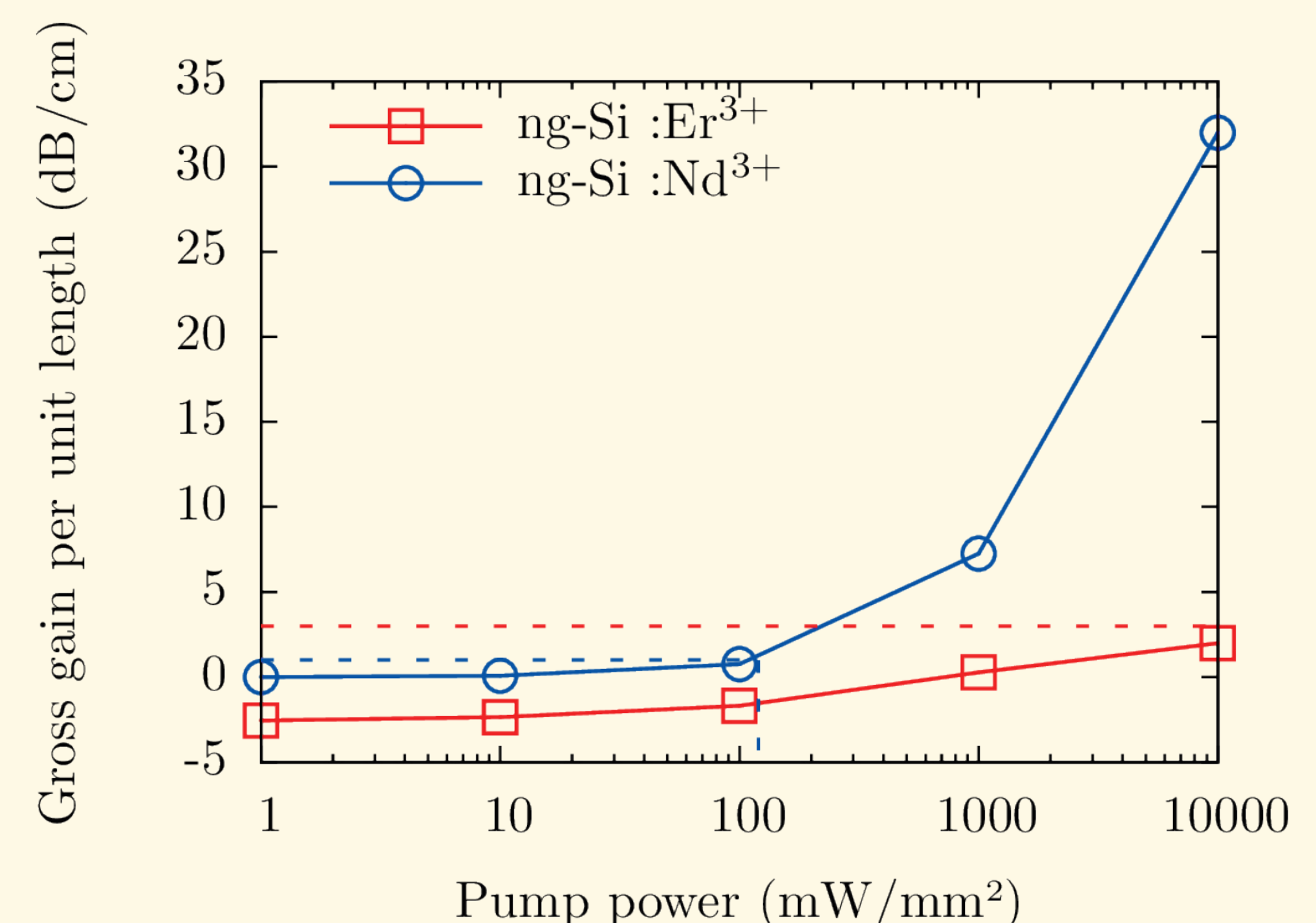
➡  $\text{Nd}^{3+}$  is a 4-level system

## ACKNOWLEDGMENT

The authors thank the French Nation Research Agency, which supported this work through the Nanoscience and Nanotechnology program (DAPHNES project ANR-08-NANO-005)

## GAIN

At the beginning of the waveguide ( $z=0$ )



Levels populations in steady states allow to calculate the gross gain. Experimental background losses are represented in dashed line (see Appl. Phys. Letter 99, 231114, 2011 for  $\text{Er}^{3+}$  and J. Appl. Phys. 114, 014906, 2013 for  $\text{Nd}^{3+}$ ). **No positive net gain with  $\text{Er}^{3+}$ . Positive net gain with  $\text{Nd}^{3+}$  for a pump power higher than 120 mW/mm<sup>2</sup>.**

## CONCLUSION

Using an original ADE-FDTD method we reach steady state of fields and populations in SRSO waveguide doped with either  $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$  ions. A positive optical gain is reached only with  $\text{Nd}^{3+}$  ions. For a pump power of 10<sup>5</sup> mW/mm<sup>2</sup> the optical gain is over 30 dB/cm. For more details see Opt. Express **22**, 12296 (2014).

To review this poster flash the QR code!

